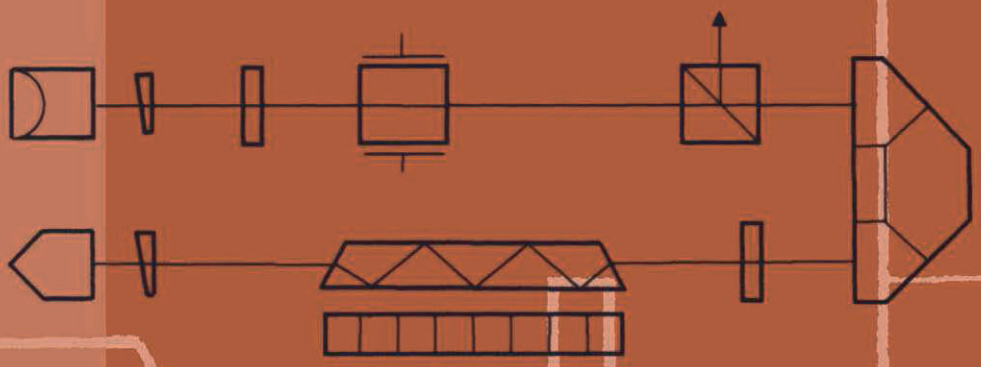
Walter Koechner • Michael Bass

Solid-State Lasers

A Graduate Text



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Walter Koechner
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Solid-State Lasers

A Graduate Text

With 252 Figures

Springer

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Cover illustration: Diode-pumped ND: YAG slab laser with positive branch unstable resonator and variable reflectivity output coupler (adapted from Figure 5.24, page 182).

Library of Congress Cataloging-in-Publication Data
Koechner, Walter, 1937–
Solid state lasers : a graduate text / Walter Koechner, Michael Bass.
p. cm.—(Advanced texts in physics)
Includes bibliographical references and index.
ISBN 0-387-95590-9 (alk. paper)
1. Solid-state lasers. I. Bass, Michael, 1939–. II. Title III. Series.
TA1705 .K633 2003
621.36′61—dc21 2002030568

ISBN 0-387-95590-9 Printed on acid-free paper.

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Printed in the United States of America.

9 8 7 6 5 4 3 2 1 SPIN 10893625

www.springer-ny.com

Springer-Verlag New York Berlin Heidelberg
A member of BertelsmannSpringer Science+Business Media GmbH

Preface

This college textbook describes the theory, operating characteristics, and design features of solid-state lasers. The book is intended for students who want to familiarize themselves with solid-state lasers beyond the level of a general textbook.

Although the book is aimed at students who are thinking of entering this fascinating field, it might also be used by practicing scientists and engineers who are changing their technical direction and want to learn more about this particular class of lasers. After studying the material presented in this book, the reader should be able to follow the scientific and technical literature and have an understanding of the basic principles and engineering issues of solid-state lasers, as well as an appreciation of the subtleties, richness of design, and operating possibilities afforded by these systems.

Solid-state lasers and systems represent a one-billion dollar industry, and they are the dominant class of lasers for research, industrial, medical, and military applications. Given the importance of solid-state lasers, a graduate text is required that deals explicitly with these devices.

Following the demonstration of the first laser over 40 years ago, an extraordinary number of different types of lasers have been invented using a wide variety of active media and pump techniques to create an inversion. As a sign of a maturing industry, laser research and engineering has developed into many specialized disciplines depending on the laser medium (solid-state, semiconductor, neutral or ionized gas, liquid) and excitation mechanism (optical pumping, electric current, gas discharge, chemical reaction, electron beam).

The development of solid-state systems represents a multidisciplinary effort and is the result of the interaction of professionals from many branches of science and engineering, such as spectroscopy, solid-state and laser physics, optical design, and electronic and mechanical engineering. Today, solid-state laser systems are very sophisticated devices, and the field has developed so far that it is difficult for a professional to enter it without prior familiarization with the basic concepts and technology of this class of lasers.

For historical reasons, solid-state lasers describe a class of lasers in which active ions in crystal or glass host materials are optically pumped to create a population inversion. Other types of lasers that employ solid-state gain media are semiconductor lasers and optical fiber lasers and amplifiers. However, since these lasers employ very specialized technologies and design principles, they are usually treated separately from conventional bulk solid-state lasers.

The design and performance characteristics of laser diode arrays are discussed in this book because these devices are employed as pump sources for solid-state

lasers. Fiber lasers are very similar to conventional solid-state lases as far as the active material and pump source is concerned. However, they are radically different with respect to beam confinement, mode structure, coupling of pump and laser beams, and the design of optical components.

The content and structure of this textbook follow closely the book by Walter Koechner entitled *Solid-State Laser Engineering* which is currently in its 5th edition. In this college text the material has been streamlined by deleting certain engineering and hardware-related details, and more emphasis is placed on a tutorial presentation of the material. Also, each chapter includes tutorial exercises prepared by Professor Michael Bass to help the student reinforce the discussions in the text. A complete solutions manual for instructors is available from textbook@springer-ny.com.

After a historical overview, the books starts with a review of the basic concepts of laser physics (chapter 1), followed by an overview of the different classes and properties of solid-state laser materials (chapter 2). Analytical expressions of the threshold condition, and gain and output of laser oscillators are derived in chapter 3. An oscillator followed by one or more amplifiers is a common architecture in pulsed solid-state laser systems to boost output energy. Energy storage and gain of amplifiers is discussed in chapter 4. Beam divergence and line width of an oscillator are strongly dependent on the spatial and longitudinal mode structure of the resonator. Resonator configuration and characteristics are presented in chapter 5. Different pump source configurations for transferring pump radiation to the active medium are discussed in chapter 6. Thermal gradients set up as a result of heat removal from the active medium have a profound impact on beam quality and output power limitations. Thermal effects and cooling techniques are treated in chapter 7. The output from a laser can be changed temporally or spectrally by Q-switching, mode-locking, and frequency conversion via nonlinear phenomena. These techniques are discussed in the last three chapters.

We would like to thank Judy Eure and Renate Koechner for typing the new material and the editor, Dr. Hans Koelsch, for suggesting a college text on the subject of solid-state lasers. We also thank Prof. D. Hagan for suggestions related to the nonlinear optics exercises and Drs. Bin Chen and Jun Dong and Mrs. Hong Shun and Teyuan Chung for testing the exercises.

Special thanks are due to our wives Renate Koechner and Judith Bass, who have been very patient and supportive throughout this project.

Herndon, Virginia — *Walter Koechner*
Orlando, Florida — *Michael Bass*
September 2002

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Introduction

Overview of the History, Performance Characteristics, and Applications of Solid-State Lasers

Major Milestones in the Development of Solid-State Lasers
Typical Performance Parameters and Applications

In this Introduction we will provide a short overview of the important milestones in the development of solid-state lasers, discuss the range of performance parameters possible with these lasers, and mention major applications. Besides the compactness and benign operating features, it was the enormous flexibility in design and output characteristics which led to the success of solid-state lasers over the last 40 years.

Major Milestones in the Development of Solid-State Lasers

Historically, the search for lasers began as an extension of stimulated amplification techniques employed in the microwave region. Masers, coined from **M**icrowave **A**mplification by **S**timulated **E**mission of **R**adiation, served as sensitive preamplifiers in microwave receivers. In 1954 the first maser was built by C. Townes and utilized the inversion population between two molecular levels of ammonia to amplify radiation at a wavelength around 1.25 cm.

In 1955 an optical excitation scheme for masers was simultaneously proposed by N. Bloembergen, A.M. Prokorov, and N.G. Basov. A few years later, masers were mostly built using optically pumped ruby crystals. In 1958 A. Schawlow and C. Townes proposed extending the maser principle to optical frequencies and the use of a Fabry–Perot resonator for feedback. However, they did not find a suitable material or the means of exciting it to the required degree of population inversion.

This was accomplished by T. Maiman who built the first laser in 1960. It was a pink ruby crystal (sapphire with trivalent chromium impurities), optically pumped

by a helical flashlamp that surrounded the cylindrical laser crystal. The parallel ends of the ruby crystal were silvered, with a small hole at one end for observing the radiation. The reflective surfaces comprised the optical resonator. The output wavelength was 694 nm. It was T. Maiman who coined the name "laser," in analogy to maser, as an abbreviation of **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation.

In early ruby laser systems the output consisted of a series of irregular spikes, stretching over the duration of the pump pulse. A key discovery made by R.W. Hellwarth in 1961 was a method called Q-switching for concentrating the output from the ruby laser into a single pulse. The Q-switch is an optical shutter which prevents laser action during the flashlamp pulse, therefore the population inversion can reach large values. If the shutter is suddenly opened, stored energy will be released in a time characterized by a few round trips between the resonator mirrors. Hellwarth initially proposed a Kerr cell, a device which rotates the plane of polarization when voltage is applied. This Q-switch, which consisted of a cell filled with nitrobenzene, required very high voltages for Q-switching; it was soon replaced by spinning one of the resonator mirrors. A further refinement was the insertion of a spinning prism between the fixed mirrors of the resonator.

The earliest application of the laser was in active range-finding by measuring the time of flight of a laser pulse reflected from a target. Investigations in this direction started immediately after the discovery of the ruby laser. Four years later, fully militarized rangefinders containing a flashlamp-pulsed ruby laser with a spinning prism Q-switch went into production. For about 10 years ruby-based rangefinders were manufactured; afterward the ruby laser was replaced by the more efficient neodymium doped yttrium aluminum garnet (Nd : YAG) laser.

Beside the use in range finders, the ruby laser was basically a research tool and, for the next 15 years, ruby lasers became the standard high-power radiation source in the visible region for research at university, government, and industrial laboratories. Applications in an industrial environment were rare, in large part due to the low-pulse repetition rate of the ruby laser (a pulse every few seconds), high cost of the equipment, and the unfamiliarity of the industry with this new radiation source. Some of the specialized applications included drilling holes in diamonds that are used as dies for drawing wires, or spot welding in vacuum through the glass envelope of vacuum tubes. Another application was stress analysis by means of double pulse holography, in which surface deformation due to stress or temperature is measured interferometrically between two pulses.

The discovery of the ruby laser triggered an intensive search for other materials, and in rapid succession laser action in other solids, gases, semiconductors, and liquids was demonstrated. Following the discovery of the ruby laser, the next solid-state material was uranium-doped calcium fluoride which was lased in late 1960. The first solid-state neodymium laser was calcium tungstate doped with neodymium ions. This laser, discovered in 1961, was used in research facilities for a number of years until yttrium aluminate garnet, as a host material for neodymium, was discovered.

In 1961, E. Snitzer demonstrated the first neodymium glass laser. Since Nd : glass could be made in much larger dimensions and with better quality than ruby, it promised to deliver much higher energies. It was quickly realized that high energy, short pulses produced from large Nd : glass lasers possessed the potential to heat matter to thermonuclear temperatures, thus generating energy in small controlled explosions. Large budgets have been devoted to the development and installation of huge Nd : glass laser systems which became the world-wide systems of choice for laser fusion research and weapons simulation. The most powerful of these systems, the NOVA laser, completed in 1985, produced 100 kJ of energy in a 2.5 ns pulse. Systems with energies ten times larger are currently under construction.

Using a ruby laser, P.A. Franken demonstrated second harmonic generation in crystal quartz in 1961. Generation of harmonics is caused by the nonlinear behavior of the refractive index in the presence of a very high electric field strength. The conversion of the fundamental wavelength to the second harmonics was extremely small because the interaction length of the beams was only a few wavelengths and the nonlinearity of quartz is very low.

Soon after these first nonlinear optics experiments were conducted it was realized that efficient nonlinear interactions require a means of achieving phase-velocity matching of the interacting waves over a distance of many wavelengths. Within a year, two basic approaches to achieve efficient harmonic generation were published in the literature. One approach, namely the use of birefringence to offset dispersion, is still the preferred method for most nonlinear processes in use today. Efficient harmonic generation was soon achieved in birefringence compensated potassium dihydrogen phosphate (KDP) crystals, a crystal which is still employed today for the generation of the third harmonic of large Nd : glass lasers. The other method, namely the use of a periodic modulation of the sign of the nonlinear coefficient to restore the optical phase, could only be realized 30 years later. In the early 1990s, lithographic processing techniques enabled the fabrication of quasi-phase-matched small crystals using electric field poling of lithium niobate.

In 1962 the idea of parametric amplification and generation of tunable light was conceived, and a few years later the first experiment demonstrating parametric gain was achieved. Commercial parametric oscillators based on lithium niobate were introduced in 1971. Damage of the nonlinear material and the appearance of tunable dye lasers led to a decline in interest in **o**ptical **p**arametric **o**scillators (OPOs) for almost 20 years. The discovery of damage-resistant nonlinear crystals with large nonlinear coefficients in the early 1990s revived interest in OPOs, and today tunable solid-state lasers covering the wavelength range from the visible to the near-infrared have found widespread applications in spectroscopy, remote sensing, and wherever a tunable radiation source is required.

The possibility of laser action in a semiconductor was explored rather early. Initially, intrinsic semiconductors pumped by an electron beam or by optical radiation were considered. However, at the end of 1962, several groups succeeded in producing pulsed output from gallium–arsenide p–n junctions cooled to cryo-

genic temperatures. About 10 years later, continuous operation at room temperature was achieved.

The first optical fiber amplifier was demonstrated in 1963 using a 1 m long neodymium-doped glass fiber wrapped around a flashlamp. However, the concept received little attention until the 1980s when low-loss optical fibers became available and the fiber-optic communications industry explored these devices for amplification of signals.

In 1964 the best choice of a host for neodymium ions, namely yttrium aluminum garnet (YAG), was discovered by J. Geusic. Since that time, Nd : YAG remains the most versatile and widely used active material for solid-state lasers. Nd : YAG has a low threshold which permits continuous operation, and the host crystal has good thermal, mechanical, and optical properties and can be grown with relative ease.

An immediate application was the replacement of ruby with Nd : YAG in military rangefinders. Since the system efficiency was about a factor of 10 higher with Nd : YAG as compared to ruby, the weight of storage capacitors and batteries was drastically reduced. This allowed the transition from a tripod-mounted unit, the size of a briefcase, to a hand-held device only slightly larger than a binocular.

Continuously pumped, repetitively Q-switched Nd : YAG lasers were the first solid-state lasers which found applications in a production environment, mainly in the semiconductor industry for resistor trimming, silicon scribing, and marking. The early systems were pumped with tungsten filament lamps and Q-switched with a rotating polygon prism. Reliability was a big issue because lamp-life was short—on the order of 40 hours—and the bearings of the high-speed motors employed in the rotating Q-switches did wear out frequently. The mechanical Q-switches were eventually replaced by acousto-optic Q-switches, and krypton arc lamps replaced tungsten filament lamps.

Up to this point, solid-state lasers were capable of generating very impressive peak powers, but average power was still limited to a few watts or at most a few tens of watts. However, at the end of the 1960s, continuously pumped Nd : YAG lasers with multihundred watts output power became commercially available.

During the first years of laser research, a particular effort was directed toward generation of short pulses from Nd : glass and ruby lasers. With Q-switching, several round trips are required for radiation to build up. Given the length of the resonator and available gain of these early systems, the pulses were on the order of 10 to 20 ns. The next step toward shorter pulses was a technique called cavity dumping, whereby the radiation in the resonator, as it reached its peak, was quickly dumped by a fast Q-switch. Pulses with a duration on the order of one round trip (a few nanoseconds) in the resonator could be generated with this method. In 1965, a technique termed “mode-locking” was invented. Mode-locking is a technique whereby passive loss modulation, with a fast response saturable absorber, or by active loss of frequency modulation, a fixed relationship among the phases of the longitudinal modes is enforced. With either passive or active mode-locking, pulses much shorter than a resonator round trip time can be generated; typically, pulses are on the order of 20 to 100 ps.

By the end of the 1960s, most of the important inventions with regard to solid-state laser technology had been made. Nd : YAG and Nd : glass proved clearly superior over many other solid-state laser materials; short-pulse generation by means of Q-switching and mode-locking, as well as frequency conversion with harmonic generators and parametric oscillators, was well understood. Xenon-filled flashlamps and krypton arc lamps had been developed as pump sources and laser diodes were recognized as an ideal pump source, but due to a lack of suitable devices the technology could not be implemented.

To gain wider acceptance in manufacturing processes, the reliability of the laser systems needed improvement and the operation of the lasers had to be simplified. During the 1970s, efforts concentrated on engineering improvements, such as an increase in component and system lifetime and reliability. The early lasers often worked poorly and had severe reliability problems. At the component level, damage resistant optical coatings and high-quality laser crystals had to be developed; and the lifetime of flash lamps and arc lamps had to be drastically improved. On the system side, the problems requiring solutions were associated with water leaks, corrosion of metal parts by the cooling fluid, deterioration of seals and other parts in the pump cavity due to the ultraviolet radiation of the flashlamps, arcing within the high-voltage section of the laser, and contamination of optical surfaces caused by the environment.

The application of solid-state lasers for military tactical systems proceeded along a clear path since there is no alternative for rangefinders, target illuminators, and designators. At the same time construction of large Nd : glass lasers began at many research facilities. Also solid-state lasers were readily accepted as versatile research tools in many laboratories.

Much more difficult and rather disappointing at first was the acceptance of the solid-state lasers for industrial and medical applications. Despite improvement in systems reliability and performance, it took more than two decades of development and engineering improvements before solid-state lasers moved in any numbers out of the laboratory and onto the production floor or into instruments used in medical procedures. Often applications that showed technical feasibility in the laboratory were not suitable for production because of economic reasons, such as high operating costs or limited processing speeds. Also, other laser systems provided strong competition for a relatively small market. The CO_2 laser proved to be a simpler and more robust system for many industrial and medical applications. Also, the argon ion laser was readily accepted and preferred over solid-state lasers for retinal photocoagulation. The dye laser was the system of choice for tunable laser sources. The entry of solid-state lasers into manufacturing processes started with very specialized applications, either for working with difficult materials, such as titanium, or for difficult machining operations, such as drilling holes in slanted surfaces; for example, in jet fuel nozzles or for precision material removal required in the semiconductor and electronics industry.

In the latter part of the 1970s, and into the 1980s, a number of tunable lasers were discovered, such as alexandrite, titanium-doped sapphire, and chromium-doped fluoride crystals. The most important tunable laser, Ti : sapphire, discov-

ered in the mid-1980s, is tunable between 660 and 980 nm. This laser must be pumped with another laser in the blue–green wavelength region. Alexandrite, first operated in 1979, has a smaller tunable output but can be flashlamp-pumped. Chromium-doped fluoride crystals such as lithium strontium aluminum fluoride and lithium calcium aluminum fluoride are of interest because they can be pumped with laser diodes.

In the late 1980s, the combination of broad band tunable lasers in combination with ultrafast modulation techniques, such as Kerr lens mode-locking, led to the development of mode-locked lasers with pulse widths on the order of femtoseconds. The pulse width limit of a mode-locked laser is inversely proportional to the bandwidth of the laser material. For neodymium-based lasers, the lower limit for the pulse width is a few picoseconds. Laser media with a much larger gain bandwidth, such as Ti : sapphire, can produce much shorter pulses compared to neodymium lasers.

Over the years, the performance of diode lasers has been constantly improved as new laser structures and new material growth and processing techniques were developed. This led to devices with longer lifetimes, lower threshold currents, and higher output powers. In the 1970s, diode lasers capable of continuous operation at room temperature were developed. In the mid-1980s, with the introduction of epitaxial processes and a greatly increased sophistication in the junction structure of GaAs devices, laser diodes became commercially available with output powers of several watts. These devices had sufficient power to render them useful for the pumping of Nd : YAG lasers. The spectral match of the diode laser output with the absorption of neodymium lasers results in a dramatic increase in system efficiency, and a reduction of the thermal load of the solid-state laser material. Military applications and the associated research and development funding provided the basis for exploring this new technology. Since the early laser diodes were very expensive, their use as pump sources could only be justified where diode pumping provided an enabling technology. Therefore the first applications for diode-pumped Nd : YAG lasers were for space and airborne platforms, where compactness and power consumption is of particular importance.

As diode lasers became less expensive, these pump sources were incorporated into smaller commercial solid-state lasers. At this point, laser diode-pumped solid-state lasers began their rapid evolution that continues today. Diode pumping offers significant improvements in overall systems efficiency, reliability, and compactness. In addition, diode pumping has added considerable variety to the design possibilities of solid-state lasers. In many cases laser diode arrays were not just a replacement for flashlamps or arc lamps, but provided means for designing completely new laser configurations.They also led to the exploration of several new laser materials. Radiation from laser diodes can be collimated; this provides great flexibility of designing solid-state lasers with regard to the shape of the laser medium and orientation of the pump beam. In end-pumped lasers, the pump beam and resonator axis are collinear which led to highly efficient lasers with excellent beam quality. In monolithic lasers, the active crystal also provides the resonator structure leading to lasers with high output stability and excellent

spatial and temporal beam quality. New laser materials, such as Yb : YAG and Nd : YVO4, that could not be pumped efficiently with flashlamps, are very much suited to laser diode pumping.

In this historical perspective we could sketch only briefly those developments that had a profound impact on the technology of solid-state lasers. Laser emission has been obtained from hundreds of solid-state crystals and glasses. However, most of these lasers are of purely academic interest. There is a big difference between laser research and the commercial laser industry, and there are many reasons why certain lasers did not find their way into the market or disappeared quickly after their introduction. Most of the lasers that did not leave the laboratory were inefficient, low in power, difficult to operate or, simply, less practical to use than other already established systems. Likewise, many pump schemes, laser configurations, and resonator designs did not come into use because of their complexity and commensurate high manufacturing and assembly costs or their difficulty in maintaining performance.

Typical Performance Parameters and Applications

Solid-state lasers provide the most versatile radiation source in terms of output characteristics when compared to other laser systems. A large range of output parameters, such as average and peak power, pulse width, pulse repetition rate, and wavelength, can be obtained with these systems.

Today we find solid-state lasers in industry as tools in many manufacturing processes, in hospitals and in doctors' offices as radiation sources for therapeutic, aesthetic, and surgical procedures, in research facilities as part of the diagnostic instrumentation, and in military systems as rangefinders, target designators, and infrared countermeasure systems. The flexibility of solid-state lasers stems from the fact that:

- The size and shape of the active material can be chosen to achieve a particular performance.
- Different active materials can be selected with different gain, energy storage, and wavelength properties.
- The output energy can be increased by adding amplifiers.
- A large number of passive and active components are available to shape the spectral, temporal, and spatial profile of the output beam.

In this section we will illustrate the flexibility of these systems and indicate the major applications that are based on particular performance characteristics.

Average Output Power. The majority of solid-state lasers available commercially have output powers below 20 W. The systems are continuously pumped, typically equipped with a Q-switch, and often combined with a wavelength converter. Continuously pumped, repetitively Q-switched lasers generate a continuous stream of short pulses at repetition rates between 5 and 100 kHz depending

on the material. Since the peak power of each pulse is at least three orders of magnitude above the average power, breakdown of reflective surfaces and subsequent material removal by melting and vaporization is facilitated.

The electronics and electrical industry represents the largest market for applications such as soldering, wire bonding and stripping, scribing of wavers, memory repair, resistor and integrated circuit trimming. In addition, industry-wide, these lasers found uses for marking of parts, precision spot and seam welding, and for general micromachining tasks. In the medical fields solid-state lasers have found applications in ophthomology for vision correction and photocoagulation, skin resurfacing, and as replacements for scalpels in certain surgical procedures. In basic research, solid-state lasers are used in scientific and biomedical instrumentation, Raman and laser-induced breakdown spectroscopy. Application for these lasers are far too broad and diverse to provide a comprehensive listing here.

Higher power solid-state lasers with output powers up to 5 kW are mainly employed in metals working, such as seam and spot welding, cutting, drilling, and surface treatment. In particular, systems with output powers of a few hundred watts have found widespread applications in the manufacturing process. The higher power levels allow for faster processing speed and working with thicker materials.

At the low end of the power scale are very small lasers with output powers typically less than 1 W. These lasers are pumped by diode lasers and have in most cases the resonator mirrors directly coated onto the crystal surfaces. The neodymium-doped crystals are typically only a few millimeters in size. These lasers have an extremely stable, single frequency output and are employed in interferometric instruments, spectroscopic systems, and instruments used in analytical chemistry. They also serve as seed lasers for larger laser systems.

The majority of solid-state lasers with outputs up to 20 W are pumped with diode arrays, whereas systems at the multihundred watt level are for the most part pumped by arc lamps because of the high cost of laser diode arrays, although diode-pumped systems with up to 5 kW of output power are on the market.

Peak Power. Pulsed systems with pulsewidths on the order of 100 μs and energies of several joules are employed in manufacturing processes for hole drilling. The peak power of these systems is on the order of several tens of kilowatts. Substantially higher peak powers are obtained with solid-state lasers that are pulse-pumped and Q-switched. For example, military systems such as rangefinders and target designators have output energies of 10 to 200 mJ and pulsewidths of 10 to 20 ns. Peak power for these systems is on the order of several megawatts. Laser generated plasmas investigated in research facilities require peak powers in the gigawatt regime. Typically, lasers for this work have output energies of several joules and pulsewidths of a few nanoseconds. The highest peak powers from solid-state lasers are generated in huge Nd : glass lasers employed for inertial confinement fusion experiments. The largest of these systems had an energy output around 100 kJ and pulsewidth of 1 ns which resulted in a peak power of 100 TW.